N71-16558

NASA TECHNICAL MEMORANDUM

NASA TM X-52907

NASA TM X-52907

PROBLEM AREAS FOR LIFT FAN PROPULSION FOR CIVIL VTOL TRANSPORTS

by S. Lieblein
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER presentation at
DGLR Symposium on VTOL Propulsion
Munich, Germany, October 22-23, 1970

OUTLINE

		Page
1.	INTRODUCTION	1
2.	PROPULSION FUNCTIONS	2
2.1	Vertical Lift	3
2.2	Cruise Thrust	3
2.3	Control Thrust	4
2.4	Transition Thrust	5
2.5	System Integration	6
3.	LIFT FAN SYSTEMS	6
3.1	Types	6
3.2	Characteristics	8
3.2.1	Integral Fan	8
3.2.2	Remote Fans with Exhaust Gas Generator	9
3.2.3	Remote Fans with Compressed Air Generator	9
4.	INSTALLED REQUIREMENTS	10
4.1	Installed Thrust	11
4.2	Noise	12
4.3	Weight and Volume	14
4.4	System Design	16
5.	FAN TRANSITION PERFORMANCE	17
5.1	Inlet Distortion	17
5.2	Back Pressure	18
5.3	Force Variations	19
6.	CONCLUDING REMARKS	20

PROBLEM AREAS FOR LIFT FAN PROPULSION FOR CIVIL

VTOL TRANSPORTS

by S. Lieblein

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

E-5614-2

1. INTRODUCTION

Vertical take-off and landing aircraft are currently under study as a means for improving short-haul intercity air transportation systems. VTOL can relieve airport congestion and reduce air time delays, and can supply access to communities currently without air transportation. VTOL proposes to accomplish these objectives through the use of new terminal sites (e.g., small airports located close to business and population centers) as well as terminal sites at existing airports. Also implied is the use of terminal area air traffic control procedures independent of conventional aircraft.

The feasibility of VTOL intercity air transportation systems has been explored by a number of American and European organizations and government agencies. It is recognized that there are many aspects to the problem of a VTOL transportation system - economic, sociological, and political, as well as technological. Examples of recent thinking on these aspects are found in Refs. 1 to 7. A total systems approach is undoubtedly required for the successful development of commercial VTOL.

A number of VTOL transport designs for intercity service have recently been studied. These studies (e.g., Refs. 2 and 8 to 13) were based on various aircraft configurations and various means of providing vertical lift (e.g., rotors, tilting propellers, and high bypass-ratio lift fans). In general, an overall impression is obtained that there currently is no outstandingly superior aircraft configuration or lift propulsion concept for the civilian VTOL mission, but, given adequate time and resources, a suitable transport aircraft could be developed.

Although there may be differences in opinion concerning the relative "readiness" for the development of VTOL intercity transports, it appears safe to state that there would be unanimous agreement that more research and development is desirable to propulsion systems for these aircraft. The general need for such research is motivated by a number of factors: (1) the large number of complex and frequently conflicting requirements placed on these systems; (2) the relatively large number of propulsion concepts potentially usable for this application; and,

(3) The critical impact of propulsion system characteristics on aircraft and overall system design and operation. Complete design and performance data and fully optimized technology are currently unavailable for the major candidate propulsion systems. What is needed is a good match between propulsion requirements and system capability.

The paper considers the low-pressure-ratio lift fan propulsion system for intercity VTOL transports. The selection of the lift fan system for vertical lift was based on several features, compared to other thruster concepts, that were considered desirable for civilian transport application. These are: (1) good potential for meeting reduced noise limitations; (2) provision for safe management of failure of power plant or thruster; (3) good passenger and airline appeal for resulting aircraft; (4) capability of high cruise speed approaching that of conventional jet liners; (5) direct use of available gas turbine technology; and, (6) elimination of mechanical transmissions.

The objective of the paper is to review the requirements and problem areas involved in the lift fan propulsion system. It will also discuss research considerations and approaches aimed at providing the design and performance data necessary for a realistic evaluation of the potential applicability of the system for use in VTOL transport aircraft. Starting with a review of propulsion functions and concepts for lift, cruise, transition, and attitude control and their interactions, the paper presents a description of various methods for driving the lift fan, and a discussion of their principal features. The second part of the paper deals with the major design requirements of lift fan systems. This section reviews major considerations in installed fan characteristics such as installed thrust, noise, weight, and component and system design. Factors in fan transition performance are also summarized. Desirable research efforts are identified throughout.

2. PROPULSION FUNCTIONS

The complex nature of the complete propulsion system for a VTOL transport aircraft is illustrated in figure 1.

The propulsion system of a VTOL transport aircraft is required to serve four functions: to provide thrust for vertical lift during takeoff, hover, and landing; to provide horizontal acceleration and deceleration as well as vertical thrust during the transition from vertical to horizontal flight; to provide horizontal thrust during the wing-supported (cruise) portion of the flight; and to provide thrust for control of the aircraft attitude and stability during the takeoff, landing, and transition flight modes. The crux of the aircraft design is to obtain an optimum integration of the four propulsion functions into the aircraft. These functions are now considered in more detail.

2.1 Vertical Lift

As indicated in the introduction, vertical thrust for take-off and landing is to be supplied by high-bypass-ratio fan stages. These fans, depending on the aircraft design approach, can be located within the aircraft fuselage or in pods along the fuselage or on the wings. The manner in which lift fans are powered, and the major requirements and problems associated with their design will be covered in later sections.

2.2 Cruise Thrust

Thrust for the wing-supported portion of the flight (climb, cruise, descent) can be supplied by conventional cruise engine concepts. Therefore, available cruise engine designs would be adequate. However, cruise engines with moderate by-pass ratios (from around 2 to 4) although good for optimum cruise performance, may be too noisy at full throttle during the transition part of the VTOL flight because of the magnitude of the exhaust velocity. Thus, it would be necessary to operate such engines at reduced power during transition, such that these engines might not provide sufficient thrust for horizontal acceleration or deceleration. In this event, horizontal thrust during transition would have to be provided by some other means. Furthermore, the full thrust capability of the cruise engines could not be made available for providing vertical lift during takeoff and landing. However, as will be indicated later, reduced-power cruise engines can also be used to supply attitude control power.

In order to meet noise restrictions, a cruise fan or cruise engine with a relatively high bypass ratio comparable to that of the lift fans can be used. However, with a high-bypass-ratio design, it becomes increasingly difficult to provide for downward thrust vectoring to assist during lift-off or for thrust reversing for horizontal deceleration during transition without large weight penalties. Other considerations involved in the use of high-bypass-ratio fans or engines for cruise are the additional drag incurred during cruise and the necessity to design for the proper match between cruise and takeoff settings. Thrust lapse rates become steeper with flight speed as the fan bypass ratio is increased. In any event, the inherent simplicity of using identical lift and cruise fans appears to warrant attention.

High-speed wind-tunnel tests with lift fan transport models are indicated to investigate aircraft cruise aerodynamics for the different cruise propulsion approaches. Such model tests can also define the effects of lift fan installations (e.g., pods or fuselage blisters) on cruise performance. Another factor of interest should be ways of utilizing cruise engine exhaust flow to provide aerodynamic lift augmentation (e.g., blown flaps) so that conversion speed can be reduced. Low conversion speeds are desired to reduce flight operating time and fuel consumption for the lift fan system, and also to minimize the effects of fan inlet flow distortion generated by inlet crossflow.

2.3 Control Thrust

Thrust for the control of aircraft attitude during takeoff, landing, and transition can also be supplied in a number of different ways. If the main lift fans are located off the center of gravity of the aircraft (i.e., in wing or fuselage mounted pods), then control in roll can be obtained by modulating the thrust of the lift fans. Control in pitch can also be obtained by thrust modulation of the main lift fans in the podded arrangement, if the fore and aft fans are located with a sizeable longitudinal separation. Thrust for yaw control can be readily supplied with exit louvers on the main lift fans in which forward-deflected thrust is supplied on one side of the aircraft and aft-directed thrust on the other side. The same effect can be obtained with fore and aft swiveling lift fans, or with differential sideways thrust deflection.

If the main lift fans are located within the fuselage of the aircraft such that they are close to the aircraft center of gravity, then fan thrust modulation no longer becomes a useful method for attitude control. In this event, it is required that either the cruise engines be used or auxiliary low-pressure-ratio fans be supplied. If moderate bypass ratio cruise engines are used, such that they are operated at low power settings and do not contribute to the horizontal acceleration or deceleration thrust requirement, sufficient power may be available for attitude control in roll, pitch, and yaw. This will require proper location on the aircraft and appropriate thrust deflection devices. However, if the cruise engines are used for attitude control purposes during transition, it is necessary that redundancy be supplied so that control power can be maintained in the event of a cruise engine failure.

Auxiliary thrusters for attitude control can be provided by independent low-pressure-ratio fans located fore and aft or at the wing tips. These control fans can be of the self-contained hub drive type, or can be tip-driven fans powered by bleed air from the main cruise or lift engine compressors, or by supply air from interconnected compressed air generators. For the latter approaches, burning can be supplied at the fam periphery to increase turbine power. However, as in the case of cruise engines, it is necessary to supply redundant units to account for failure of any one of the thrusters. For purposes of engine maintenance and installation, it would be desirable to have the auxiliary control fans the same size as the main lift fans. Discussions of attitude control systems are given in Refs. 14 and 15.

High-velocity reaction jets are not considered desirable for commercial VTOL transports because of the associated high noise and high bleed flow rates required.

2.4 Transition Thrust

During the transition from vertical to horizontal flight, vertical thrust will be supplied by the lift fans. Horizontal thrust for acceleration can be provided in any of the four ways illustrated in Fig. 2. In parts (a) and (b), the main lift fans are used to supply this function. In the first approach, exit louvers or other deflecting surfaces are attached to the fixed fans with appropriate capability for forward and rearward thrust vectoring. In the second approach, the entire fan is swivelled fore and aft to provide the required thrust vector.

Parts (c) and (d) of Fig. 2 illustrate the use of a cruise fan for supplying horizontal thrust during transition. This can be accomplished either with a fixed fan with provision for thrust deflecting and reversing as suggested in part (c), or by a tilting fan that can be rotated more than 90^{o} to provide either forward or rearward thrust components (part (d)). A rotatable lift fan is probably more amendable to a fuselage mounted installation. It might also be possible to obtain required thrust deflecting and reversing with wing flaps in conjunction with fixed cruise propulsion units.

The major aerodynamic problem involved in horizontal thrust vectoring with lift fans (Figs. 2(a) and (b)) during transition is illustrated in Fig. 3. This figure poses questions of limiting performance as expressed by the variation of percent ideal gross thrust with deflection angle for both swivelling fans and louvered fans. For accelerating thrust, the swivelling fan will have good inflow performance, but only up to some point, due to interference effects between adjacent fans and the enclosing pod. For louvered fans with fixed cambered vanes, however, vane drag losses will generally continuously increase with deflection angle, and can become quite severe when excessive flow separation occurs at large vane angle of attack.

If decelerating thrust is required, the performance of the swivelling fan is expected to decline with increasing negative deflection angle, since the incoming air must now be turned more than 90^{o}. The thrust losses of the louvered fans will also increase with negative deflection angles, since once again the vane drag will increase as the vane angle of attack becomes unfavorable.

Other factors involved in the comparison include the longer pod length and poorer pod aerodynamics with the swivelling fans, the added weight of the louvers for the fixed fans, and also the possible effects of louver deflection on fan back pressure and gross thrust for the fixed fans.

It is clear therefore that significant aircraft configuration studies are required to establish - and minimize - the thrust vectoring limits required for the lift fans during transition. At the same time, comparative evaluation of thrust performance variations, as well as concepts for improving performance, are required for the swivelling and fixed fan approaches. Comparative data on the installation penalties involved in each approach would also be needed.

2.5 System Integration

In view of the large number of approaches possible for the lift, cruise, transition, and control functions, it is not difficult to appreciate the dilemma of the aircraft designer in attempting to select and integrate the various elements of the propulsion system in the aircraft installation. Furthermore, the manner in which the propulsion functions are provided for will exert a substantial influence on the installation of the various propulsion system components as well as the overall configuration for the aircraft. In short-term approaches, VTOL transport configurations can be designed based on available, or near-available, cruise propulsion engines. However, for the long-range solution, it is clear that more studies and experiments are needed to define the optimum propulsion elements required to produce the best aircraft with optimum integration of all propulsion functions.

3. LIFT FAN SYSTEMS

With the adaption of the high-bypass-ratio (low pressure ratio) fan stage as the basic thrust device for vertical lift, it must be decided how the fan rotor is to be powered. The various types of fan systems and their principal characteristics will now be discussed.

3.1 Types

Fan systems are identified by the relation between the fan and the powerplant supplying power to the fan drive turbine. Two general types are currently recognized, the <u>integral</u> and <u>remote</u> systems. An isometric drawing of the general configuration for these systems is shown in Fig. 4. No inlet or exhaust sections are included for the fans or powerplants.

The integral coaxial system (Fig. 4(a)) is similar to a high-bypass-ratio turbofan engine in which the fan is powered by a coaxially-mounted gas turbine engine. The principal virtue of the integral lift fan concept is the inherent simplicity of working with self-contained independent units. This provides a simple reliable means for safety through redundancy in the event of the failure of either the powerplant or the fan. Independent units are also easy to swivel and can provide for varying amounts of control thrust modulation. This type of fan has been promoted by Rolls-Royce Ltd. (16 to 21) and also by the Pratt and Whitney Aircraft Company (22).

In the remote type (Figs. 4(b) and (c)), the fan and its drive turbine are separately located from the powerplant, and power is delivered pneumatically to the fan drive turbine located at the outer periphery of the fan (tip turbine drive) The drive turbine can be powered either by the exhaust gas from a hot gas generator (Fig. 4(b)), or by high-pressure air from a compressed-air generator (Fig. 4(c)). In the latter case, an option exists to deliver the compressed air directly to the fan turbine, or to raise it to a high temperature in an auxiliary combustor at the fan before delivery to the drive turbine.

Remote powerplants are considered as candidates for lift fan systems for a number of reasons. First, interconnecting can be provided for the powerplants. In so doing, power can continue to be supplied to all fans in the event of the shutdown of one of the powerplants, and lift unbalance can be avoided. Interconnecting can allow for fewer powerplants than fans, and can readily provide for the use of the main powerplant systems to power auxiliary attitude control fans and cruise fans, if needed. In all cases, however, appropriate valving and controls will be required for proper system operation and reliability (e.g., powerplant start up, emergency shutdown, and fan shutdown).

The second principal feature of the remote system with tip-turbine driven lift fans is the potential for providing a substantially shorter fan axial depth than in the case of the integral fans. However, it is not clear at this time whether the short depth potential can be fully realized because of the uncertainty in the amount of acoustically-treated duct length that might be required to satisfy perceived noise limitations.

The principal factor in consideration of the compressed air remote system (Fig. 4(c)) is illustrated in Fig. 5. The figure shows the relative variation of the flow area of the duct between the air generator and the lift fan and the inlet area of the scroll that feeds the tip turbine of the fan compared to the case of the straight exhaust gas generator (Fig. 4(b)). Moderate supply pressures of the order of 6 to 8 atmospheres can reduce duct and scroll areas to around a third to a quarter of those for the exhaust gas generator arrangement. The reduced areas result from both an increase in fluid density and a decrease in the required turbine flow rate (for the same developed power). These features, however, are obtained at the expense of the added complexity of an additional combustor and fuel system for each fan. However, the temperature of the interconnecting duct will be relatively cool (i e., heat of compression).

3.2 Characteristics

3.2.1 Integral Fan

The component arrangement of the integral coaxial fan will depend to a large extent on the magnitude of the compressor pressure ratio. If a relatively low pressure ratio can be accepted (say, around 4 to 6), a short compact configuration could be obtained with conventional axial components. Specific fuel consumption would be compromised in this case. If long fan operating times are indicated so that fuel consumption is critical, then compressor pressure ratio would have to be increased. However, in order to maintain short axial depth, a reverse flow combustor might be used as illustrated schematically in Fig. 6. The cross-hatched sections in the fan duct indicate acoustic treatment.

In general, no basically new component concepts or technology should be required for the coaxial lift fan concept. There also exists a good potential for providing a capability for significant overthrust in emergency situations through short-time overspeed and overtemperature operation. The extensive use of composite materials is also potentially possible with the integral fan in view of the relatively cool temperatures of the entire fan stage portion.

The principal problem areas identified with the design of integral fans are the fan rotor and the fan drive turbine. Good inlet flow distortion tolerance and good efficiency are required for the fan rotor, especially since high blade aspect ratios will probably be desired for reduced noise (high blade passing frequency). Aeroelastic difficulties might also be present. The use of the rotor flow-passage splitter (as shown in Fig. 6) and separate blade designs for the two sections can alleviate much of the difficulties that would arise at the hub with such low hub-tip ratio configurations. However, the core passage blading and the compressor must also be designed to accept the inlet flow distortions that occur during transition flight.

Since the diameter of the fan drive turbine will be considerably smaller than the fan rotor, it will be necessary to develop high-work turbines in order to reduce the number of required turbine stages (reduce axial depth and weight). In this respect, high fan rotor speed is desired, but this must be compromised with the noise requirement.

If a reverse-flow burner is used, such as in Fig. 6, minimizing pressure losses becomes an important problem. Means of maintaining easy component accessibility and reducing costs also become significant considerations with this arrangement.

3.2.2 Remote Fans with Exhaust Gas Generator

A schematic cross section of a lift fan with a tip turbine drive is shown in Fig. 7(a). The fan design involves a single wheel which carries the fan rotor blades and the tip turbine buckets mounted around the periphery of the fan. Also shown is the scroll which feeds the hot gas to the turbine nozzles. Figure 7(b) shows a schematic cross section of a straight turbojet exhaust gas generator that could be used to drive the tip turbine fan. The tip turbine fan driven by an exhaust gas generator has received considerable attention by the General Electric Company (23 to 29).

The principal consideration in favor of the remote exhaust gas generator system is the existence of available gas generator engine technology and tip-turbine fan design experience. These can provide for a relatively early flight aircraft application. However, if the high exhaust temperatures of advanced turbojet gas generators are accepted, scroll and tip turbine construction, cost, reliability, and limited over-temperature capability for emergency overthrust can be problem factors.

For advanced gas generator systems, increased exhaust temperatures may cause further difficulties in the design of the fan turbine scroll and bucket attachment. Accordingly, it may be desirable to consider a gas generator with a low bypass ratio, as shown in Fig. 7(c), in order to provide for some lower-temperature air that could be used for cooling purposes. The bypass air can be bled off directly behind the low spool (configuration A), or mixed with the core exhaust (configuration B), or allowed to flow coaxially with the discharge duct (configuration C). Engine component technology is also generally available for this approach.

In either approach the use of an exhaust gas generator will require the use of relatively high-temperature valving and large-diameter high-temperature ducting, which may be undesirable in a civilian passenger transport.

3.2.3 Remote Fans with Compressed Air Generators

A schematic cross section of a tip turbine driven lift fan based on a compressed air generator is shown in Fig. 8(a). The principal difference between this configuration and the configuration for the exhaust gas generator power supply (Fig. 7(a)) is a two-stage turbine and a smaller scroll diameter. Both of these are the result of the higher fan turbine inlet pressure level provided by the compressed air supply. The smaller scroll size in conjunction with control over the inlet gas temperature in the auxiliary burner can make for a lighter and easier scroll design. However, if the turbine gas temperature is raised to above the 1900° R level, design difficulties and complex cooling requirements would probably result.

A primary design problem created by the compressed air approach is the relatively short height of the turbine flow passage (order of 1/3 to 1/4 of height in case of exhaust gas generator arrangement). With such short blade heights, poor interstage leakage and dimensional control may seriously affect turbine performance. Furthermore, with the relatively high pressure existing at the outlet of the first nozzle row, a difficult problem is raised to minimize the leakage of hot gas into the fan airstream just upstream of the rotor. Such leakage will have deleterious effects on the performance of both the fan stage and the tip turbine.

The fan combustor design may also be difficult because of the need to reduce length and weight and to avoid adverse temperature profiles at the inlet to the scroll.

A schematic cross section of a compressed air generator concept is shown in Fig. 8(b). In this configuration the low compressor is designed to provide the required pressure for the supply flow to the fan turbine. Again, a folded combustor is shown to reduce axial length. The residual thrust from the core discharge can be used to provide vertical thrust, or in conjunction with a swivel nozzle, can be used to provide vectored thrust during transition.

For situations in which relatively large amounts of emergency overthrust capability are required (e.g., interconnected system with few air generators and larger number of fans), an interburner can be added between the high compressor drive turbine and low compressor drive turbine of the two-speel configuration shown in Fig. 8(b). However, it is not clear whether the addition of such a capability in this manner warrants the added complexity of another fuel system and additional flow pressure drop when the unit is in normal operation.

It is thus seen that there are a number of ways to drive the lift fan - each has its advantages and disadvantages, which will depend on the specific requirements of the propulsion system and the installation approach in the aircraft. Detailed comparative evaluations of these drive approaches would be of interest to define optimum cycle, weight, and dimensional characteristics, as well as to identify potential gain and problem areas for the system components.

4. INSTALLED REQUIREMENTS

There are a number of factors associated with the installation and operation of the lift fans in the aircraft that can exert a significant effect on the selection and specific design of the lift fan system. Examples of such factors are installed thrust, noise, system weight, and service requirements.

4.1 Installed Thrust

The design installed thrust of the lift, cruise, and control systems will depend on the requirements of the specific functions of the system. In all cases, a knowledge of the aircraft configuration and mission is required. However, the aircraft design itself will depend upon the installed characteristics of the propulsion system, so that an iterative process is indicated.

The total design installed takeoff thrust for the main lift fans will depend upon a large number of factors such as: aircraft gross weight; vertical thrust contributions of the cruise and attitude control units; amount of fan thrust modulation required for attitude control; design takeoff ambient temperature and altitude; allowable emergency rating in the event of power plant failure; installation losses; desired vertical acceleration with power plant out; the number and arrangement of fans and power plants used; and the criteria adopted for "engine-out" safety (e.g., number of units that can fail, powerplant and fan failure, or powerplant-only failure). The latter is a matter for airworthiness standards. However, the impact of different safety criteria and provisions on propulsion system and aircraft design can be quite marked, and should be documented. Furthermore, these effects may not be equal for the different lift fan systems. For civil applications, it is believed that provision should be made for the safe shutdown of a fan as well as a powerplant.

An illustration of the effect of provision for emergency shutdown of a fan or powerplant on the amount of excess thrust or power that must be contained in the fan system installation is given in Figure 9. The plot shows variation in required excess fan thrust or excess engine power with number of fans or powerplants for several limiting situations. The upper solid line refers to the case of fan shutdown in which the surviving fans must supply restoring moments as well as lost lift, as would be the situation with fans in outboard wing pods. If the fans are located on the center of gravity, the other limiting case of supplying only lost lift is given by the lower solid line. These curves apply to the case of a fan out regardless of how the fan is driven.

The dashed lines represent the situation for the powerplants. If the powerplant is integral with the fan, the upper dashed curve is obtained. If the powerplants are interconnected so that all fans continue to operate (no force unbalance), then the lower dashed curve is obtained. This indicates that if provision is allowed for powerplant shutdown only, then the installed excess power requirement can be reduced for a given number of interconnected powerplants, or, coversely, the number of interconnected powerplants can be reduced for the same value of installed excess power. In all situations, the required excess of power is slightly greater than the corresponding required increase in thrust since the ratio of power-to-thrust increases as the speed and pressure ratio of the surviving fans is increased to supply the required total thrust.

It should be noted that the normal operating thrust (takeoff lift) and the thrust value for which the fan system is noise rated may not necessarily be the same as the value of installed thrust for which the system is sized. This is illustrated in Figure 10 which shows a typical fan operating line. Under normal conditions with all units operating, a nominal thrust will be required for lift-off (lower dot), with excursions as needed for control thrust modulation $(\Delta F)_{c,n}$. With a fan or powerplant out, an increase in fan thrust $(\Delta F)_o$ will be required to the nominal value indicated by the upper dot. Thrust modulation for control will again be needed $(\Delta F)_{c,o}$, although the value may be somewhat less than that for normal operation. A maximum thrust capability indicated by the uppermost dashed line will therefore be required for safety considerations. If an emergency overthrust capability $(\Delta F)_E$ is available, the fan design thrust requirement is reduced to the level of the dot-dash line. The importance of being able to provide for a significant amount of emergency overthrust in the fan design is clearly evident as a means for reducing installed thrust. Values of ratio of sea level standard installed vertical thrust to aircraft gross weight for large VTOL transports are of the order of 1.3 to 1.6.

Normal fan operation will be at some part-speed point, the magnitude of which will be determined primarily by the installed provisions for "engine-out" safety and total number of fans used. If relatively few fans are used, the normal operating speed may be sufficiently different than the design speed to warrant off-design consideration in the design of the fans.

4.2 Noise

For lift fan systems, the principal noise contributors are recognized to be the rotational noise and the exhaust flow noise from the lift fan and its drive turbine. The compressor in the coaxial gas generator may also be a significant noise source if a very high tip speed is used. For remote power systems, the additional noise sources from the drive powerplant must be considered. Exhaust velocities for the compressed air generators will have to be kept relatively low, which will result in a low residual thrust and a large exhaust duct. Since these powerplants will most likely be oriented horizontally in the aircraft, inlet and exhaust duct acoustic treatment can be effectively used to suppress the machinery noise. However, such provisions constitute installation penalties for these systems.

If it is assumed that powerplant noise can be effectively reduced to below the level of the fan noise, then the design of the lift fan must be controlled to satisfy noise limitations. According to current experience, fan rotational noises appears to be greater than fan exhaust noise for current VTOL fan designs. However, if it is further assumed for the moment that fan rotational noises can be reduced to the exhaust flow noise level, then an initial appraisal can be made of the impact of noise restrictions on fan design by analyzing the fan exhaust flow noise (i.e., the noise floor level).

Although it has not yet been conclusively confirmed, it is believed that fan exhaust flow mixing noise (low velocity jet noise) is proportional to the 8th power of the exhaust velocity. From an extrapolation of the standard jet noise correlation (SAE AIR 876) to low velocities according to the 8th power, calculated variations of total perceived exhaust flow noise with number of lift fan engines containing both fan and turbine exhaust (velocities V_F and V_T, respectively) were determined. Several fan stage pressure ratios, as shown by the solid curves in Figure 11 are included. Also shown on the figure by the dashed lines are values of exhaust noise required to meet several proposed perceived overall aircraft noise limits. The plotted values of exhaust noise limits were obtained from the consideration that with fan rotational and exhaust noise equal, the magnitude of the exhaust noise limit will be 3 PNdB lower than the overall limit. For the jet noise model of Figure 11, fan stage pressure ratios of the order of 1.15 to 1.20 are indicated, depending on the specific overall noise limit selected. However, since fans will most likely be noise rated at the normal maximum thrust point (Fig. 10), the allowable design (installed thrust) pressure ratio will be somewhat greater than the values determined by the noise limits.

A more recent calculation of exhaust flow noise based on an improved density factor indicated curves of perceived noise against number of fan engines that were about five PNdB lower, on the average, than the values shown in Figure 11. Thus, maximum allowable stage pressure ratios might be of the order of 1.20 to 1.25, as far as jet noise is concerned.

In order to achieve fan noise limitations as indicated above, fan rotational perceived noise must be reduced to the level of the exhaust flow noise. The control of fan rotational noise is a complex matter because of the large number of factors that can affect the noise generation: tip speed, blade loading, flow turbulence, rotor tip flow, and blade-row geometry (number of blades, distance between rows, lean angle, etc.). Of particular importance in lift fan system design is rotor tip speed. High values of tip speed are desired to reduce the number of drive turbine stages or increase turbine efficiency for fixed number of stages. Current knowledge indicates that acoustic treatment of the fan duct will be necessary to achieve the desired reduction in rotational noise.

Research on lift fan noise is currently required in the following areas:

(1) Fan exhaust flow noise floor level with effects of coaxial annular streams of different temperature and with thrust deflecting devices.

(2) Relations between rotational noise and fan stage design parameters and geometry.

(3) Weight, length, and noise-reduction tradeoffs for duct acoustic treatment.

(4) Studies of the noise footprints of the total propulsion system during transition for the various lift fan system concepts.

4.3 Weight and Volume

The importance of lift fan system weight in VTOL transport design is illustrated in Figure 12. Gross weight for a 100-passenger aircraft is plotted on the ordinate. The abscissa represents the ratio of installed thrust to weight of the lift fan system installation, which includes the dry weight of the thrusters and powerplants plus the weights of the various installation components (containing pod or other mounting structure, inlets, exhaust ducts and deflectors, interconnecting duct system, and control system). Lift fan system specific fuel consumption is included as a parameter.

It is seen from the figure that aircraft gross weight tends to increase rapidly as system installed thrust-to-weight ratio is reduced, while the sensitivity to specific fuel consumption shows little variation. The calculation was made for a simplified aircraft model which included provision for crew, cargo, cabin equipment, airframe structure, and cruise propulsion and fuel.

Projected trends in lift fan system uninstalled thrust-to-weight ratio are presented in Figure 13 together with variations for other types of engines. The available data points for lift fans are for coaxial and gas generator-tip turbine systems in the thrust range of 10 000 to 15 000 pounds. The band presented for the lift fan system weight is the author's estimate of realistic values for fan systems in commercial use for which good maintainability and reliability are required. With indicated uninstalled thrust-to-weight ratios around the

10 to 12 level, and with installation weight additions of say around 25 to 50 percent, installed lift fan system thrust-to-weight ratios of the order of only 7 to 9 may be achievable in the near future. According to Figure 12, such values will result in a relatively heavy aircraft. It would seem, therefore, that considerable attention should be given to the impact of lift system dry weight and installation weight on aircraft design.

In this respect, reduction in dry lift system volume might be as important as reductions in system dry weight because of the compounding effect of volume on installation weight. For the fans, low volume is dependent on achieving high ratios of thrust/airflow and airflow/frontal area. Thrust/airflow is determined by fan stage pressure ratio and efficiency, and airflow/frontal area will also depend on fan pressure ratio. Fan volume might also be dictated by inlet section and acoustic treatment requirements. Low powerplant size is favored by reduced power requirement and by compact components and high turbine inlet temperature.

The importance of fan stage pressure ratio in influencing lift fan system volume and weight can be inferred from Figure 14*. Low fan pressure ratio produces a large fan diameter and volume but requires a smaller drive powerplant. A somewhat lower fuel consumption also results. The trend is reversed for high fan pressure ratios, so that for a given aircraft design and thrust level, there is probably an optimum fan pressure ratio for minimum installed system weight. However, since fan pressure ratio will be determined by noise limitations, system research effort should be directed toward minimizing component weight and volume for the selected pressure ratio levels.

Low component weight will depend on high areodynamic loading, lightweight materials, and efficient structural design. Unlike conventional cruise engines, lift system components must be designed to satisfy cycle life criteria. Annual flight operations, for example, might involve many thousands of start-stop cycles, but only around a hundred hours of accumulated time for the lift system. It is also desirable to design critical lift system components to permit operation for a brief period of time at a significant overthrust condition (say 10 percent) during emergency "engine-out" situations. As indicated earlier, an emergency overthrust rating is desirable to reduce installed thrust level. In the event of the use of the emergency rating, it is

---

*Specific values of the parameters in Figure 14 at the reference fan pressure ratio, expressed as a ratio of fan thrust are: fan tip frontal area, 1.44×10^{-3} ft^2/lb; airflow rate, 0.0488 (lb/sec)/lb; drive power, 0.727 HP/lb; and specific fuel consumption, 0.4 (lb/hr)/lb.

probable that inspection of sensitive system parts will be required.

Lift fan system thrust-to-weight will also depend on the size of the fan, which is related to the number of fans used (e.g., Fig. 9).

4.4 System Design

Unfortunately, the elements that favor low system weight and volume are generally inconsistent with good fuel economy, good maintainability, and high reliability characteristics. According to Figure 12, aircraft gross weight does not appear to be highly sensitive to lift system specific fuel consumption. However, high system reliability and good overhaul and maintenance characteristics are essential for economical commercial operations. Dispatch reliability in VTOL operations will be particularly important in view of the overall complexity of the propulsion systems and the large number of units and components involved. Systems based on more conventional components and configurations for which a reliability history or experience is available might therefore offer a better development risk in the long run.

In view of system complexity, rapid event occurrence, and heavy pilot work load, it is clear that an automatic control system will be required. The control system would handle normal engine operating functions (startup, check out, throttling), attitude control requirements, "engine-out" trim procedures, and possibly prescribed transition flight path control. An extremely sophisticated integrated control and propulsion system arrangement will therefore be required which will also have to have a high degree of reliability.

Another common factor for fans involved in the attitude control function is the thrust acceleration time response. Preliminary estimates indicate desired response times of the order of 0.3 second for a 10 to 25 percent thrust increase for a large VTOL transport. Since response time varies directly with moment of inertia of the rotating components and inversely with the accelerating torque, component size and mass will be significant factors. The largest determinant of rotating inertia is component size, since moment of inertia for a given configuration will vary with the 4th to 5th power of the diameter. Thus, the number of fans used for given total thrust will be the most significant design control element for response time. However, for a given fan thrust level, any reduction in rotating mass will directly benefit thrust response time.

The design of the lift fan propulsion system to meet desired installed characteristics is thus seen to represent a form of "eternal triangle" with high performance at the apex of the triangle and low noise and low cost at the two lower ends of the triangle. High performance characteristics, which may be in conflict within themselves, are generally not compatible with achieving low noise levels and low cost. Thus, VTOL propulsion system design will be an exercise in compromises and tradeoffs.

5. FAN TRANSMISSION PERFORMANCE

There are a number of research problem areas associated with the performance of lift fans during the transition between horizontal and vertical flight. These problems arise as a result of the orientation of the inlet of the fan with respect to the oncoming flow, the functions that the lift fan are required to perform, and the large masses of air that are set in motion by the operation of the fans. These problems, which are similar in principle to those encountered with earlier experimental VTOL lift fan aircraft, are expected to be more severe in large VTOL transports because of the larger number of fans involved and the need for achieving optimized performance.

5.1 Inflow Distortion

A problem that was recognized in early considerations of lift fans is that of inlet flow distortion and performance loss due to the change in inflow direction during forward flight. The nature of this crossflow effect on fan inflow is illustrated in Figure 15. Under static conditions (zero forward flight), the flow into the inlet is largely axisymmetric. However, under crossflow conditions during transition (Fig. 15(a)), an acceleration and deceleration of the flow occurs over the forward portion of the inlet, which generally leads to a local separation of the flow as indicated by the shaded area. Flow separation can also occur on the aft side of the centerbody. At the same time, the incomplete turning of the inflow into the fan passage results in an "advancing-retreating" orientation for the rotating rotor blades as indicated by the sketch of Figure 15(b) The circumferential variation in approach angle in conjunction with the circumferential variation in meridional velocity then produces a circumferential variation in change in incidence angle on the rotor.

The combination of flow separation and rotor inlet flow maldistribution can result in a deterioration of fan efficiency and thrust as flight speed is increased. There is also concern that the inlet flow distortion and the increased flow turbulence due to poorer fan performance can measurably increase the fan noise radiation during transition.

Many experimental investigations of flow distributions in lift fan inlets in crossflow have been conducted in the past.[27, 30 to 33] Current effort at NASA is directed toward developing analytical techniques for determining inlet flow distributions and surface boundary layer development. A potential flow solution for the design and analysis of axisymmetric inlets in static flow is described in Ref. 34. Preliminary discussion and comparisons with experimental data for the comparable crossflow solution are given in Ref. 35. Boundary layer theory and experiments aimed at the prediction and control of flow separation in lift fan inlets in crossflow are also needed.

An example of the calculated variation in surface velocity over the forward arc of a lift fan inlet in crossflow is shown in Figure 16 for several crossflow velocities. The inlet section was originally designed for the avoidance of surface velocity deceleration under static conditions ($V_\infty = 0$). The sharp velocity acceleration and deceleration on the surface resulting from the crossflow is clearly seen. More recent calculations based on an improved compressibility correction indicate even higher theoretical peaks in crossflow than shown in the figure.

Calculated variations of change in incidence angle relative to the static case for a hypothetical "disturbance-free" rotor located at the inlet station ($S = 0$ in Fig. 16) are illustrated in Figure 17. (A "disturbance-free" rotor is one that produces no change in the upstream flow.) Significant unsymmetrical changes in rotor incidence angle may therefore occur for a real fan. However, the presence of the rotor and its pressure field will undoubtedly disturb the incoming flow to some extent, so that the net effect on the rotor operation is unknown (possibly not as severe as suggested by the idealized calculations). Such variations in rotor incidence angle will give rise to circumferential variations in rotor blade loading and outlet flow conditions. Thus, a significant potential exists for an increase in rotor-generated noise during the transition flight regime if fan speed is maintained constant.

5.2 Back Pressure

Variations in the static pressure of the discharge flow during transition can also affect fan stage performance. Such changes in back pressure can arise from interactions between the fan and drive-turbine exhaust streams and from interactions between these streams and the crossflow air stream (Fig. 15(a)). Another potent source of back pressure variation is any thrust deflection device that is used at the exit of the fans. For example, rearward deflection of exit louvers would tend to increase the fan back pressure, while discharge flow interactions might tend to decrease the back pressure.

The effect of variations in fan back pressure on the gross thrust of a fan will depend on the fan stage performance map and the operating point selected for the fan design. Figure 18 illustrates a possible variation in fan gross thrust with exit static pressure for a fan designed for maximum gross thrust at ambient duct exit pressure at takeoff.

It may therefore be important to know the back pressure conditions over which a fan will be operating for the particular installation of the fan.

5.3 Force Variations

The aspect of the fan flow during transition that has received considerable attention is the interaction of the fan flow with the flow around the aircraft. Numerous wind tunnel tests of fan-in-wing, fan-in-pod, and fan-in-fuselage configurations have been conducted,[36 to 41] and a good understanding of the effects of fan flow on aircraft induced lift, drag, and moments has been obtained (e.g., Refs. 42 to 45). A strong effort in lift-fan aircraft aerodynamics has been mounted in particular by the NASA Ames Research Center.

During transition, drag contributions are provided by the ram (momentum) drag of the fan inflow (flow rate times flight speed) and the fan mounting structure (e.g., wing or fuselage pod). In this respect, the lower the allowable fan pressure ratio, the higher the flow rate for a given thrust (Fig. 14) and therefore the higher the ram drag. Pod drag is determined by the geometry of the body containing the fans, the auxiliary devices for the fan (e.g., louvers, cover doors), and the interaction between the fan flow and the normal flow around the body.

For the lift and thrust forces, concern is over both thrust degradation and induced lift forces generated by the interaction between the fan flow and the flow over the aircraft aerodynamic surfaces. These induced forces can be negative or positive, depending on the number of fans and their location on the aircraft. Fan thrust degradation is measured with respect to ideal fan thrust which is obtained from the conditions of no inlet total pressure loss, constant total pressure ratio across the rotor, and ambient discharge pressure. Ideal fan gross thrust increases with increasing forward flight speed.

Since aircraft wing lift increases with flight speed, a decrease in fan vertical thrust should be allowable as conversion speed is approached. However, the acceptable thrust degradation for an aircraft design will depend to a large extent on the transition flight profile and associated requirements for thrust magnitude and deflection. Parametric analysis of transport aircraft transition flight for various propulsion system arrangements and flight constraints would be helpful in evaluating the effect of fan transition performance on aircraft design and operation.

Even if transition flight dynamics can allow a sizeable degradation in fan thrust as flight speed is increased, it appears that it would always be desirable to press for minimum fan pressure losses in crossflow. Reduction in crossflow pressure losses will reduce fuel consumption and noise generation arising from reduced efficiency. The maintaining of good fan performance throughout the transition speed range can also provide a potential for controlled thrust reduction for noise abatement procedures.

Wind tunnel tests of a 15-inch-diameter model lift fan are currently in progress at the NASA Lewis Research Center with the setup shown in Figure 19. The fan rotor is driven by a compact two-stage turbine located within the hub of the fan. The turbine is powered by high-pressure air supplied through several struts across the fan passage. This configuration provides for a fan unit with coaxial discharge flows (as in the case of a real fan) that can be installed completely within the supporting aerodynamic body. Measurement is made of wing lift, drag, and pitching moment, and of fan performance, internal flow distributions, and axial force. Maximum tunnel air speed is 170 mph. The purpose of these initial tests is to investigate in detail the flow and force distributions generated by the fan flow in crossflow and to determine the nature and magnitude of the factors influencing thrust variation. A subsequent setup will contain a fan-in-pod arrangement for tests of performance and distortion tolerance of fan configurations involving low noise features. Variables that can be considered include rotor tip speed, rotor aspect ratio, inlet design, and separation control schemes.

Experiments are also needed to investigate tandem fan performance and flow interactions in several multiple=fan pod configurations. Concern here is for variations in fan inflow rate and performance with fan location, with spacing between fans, and with bounding surfaces. Thrust deflecting approaches as illustrated in Figure 2 should also be included.

6. CONCLUDING REMARKS

In summary, it may be said that the principal problems in VTOL lift fan propulsion lie in the three general areas of:

- Optimum integration of the lift, cruise, control, and transition functions.

- Specific design of the fan stage and selection of its drive system.

- Fan performance and noise in crossflow.

Considerable trade-off evaluations and compromises may be necessary to define the most suitable lift fan system design for VTOL commercial applications.

Although many, VTOL fan propulsion problems are not considered insurmountable. In this respect, it should be recognized that the current identification of propulsion problem areas is basically qualitative. Such qualitative evaluations may tend to generate undue concern because of the absence of quantitative data. It is quite likely that as actual research and technology efforts are accelerated, many of the current concerns may be dissipated.

A well-defined and well-integrated lift fan propulsion research effort can do much to enhance the early development of civil VTOL transports. In particular, research and analysis are needed to determine the relative importance of the various problem areas - which factors have a large or small impact on overall design and performance - and to provide quantitative data for the key input factors that will be involved in system selection and design. The traditional role of research in devising new concepts and solving specific problems will also be helpful.

REFERENCES

1. Brown, D. G.: The Case for V/STOL Aircraft in Short-Haul Transportation. Paper 700333, SAE Apr. 1970.

2. Jagger, D. H.; and Kemp, E. D. G.: The Potential and Development of a V/STOL Inter-City Airliner Aircraft Eng., vol. 42, no. 1, Jan. 1970, pp. 6-13.

3. Simpson, R W.: The Outlook for Future Commercial VTOL Transportation. Paper 69-198, AIAA, Feb. 1969.

4. Asher, N. J.: Demand for Intercity Passenger Transportation by VTOL Aircraft. J. Aircraft, vol. 6, no. 5, Sept.-Oct. 1969, pp. 452-456.

5. Stultz, J. T.; and Dorozenski, R. W.: V/STOL Considerations in Air Traffic Control. Paper 69-1055, AIAA, Oct. 1969.

6. Hayward, D. W.: Study of Aircraft in Short-Haul Transportation Systems for 1985. Paper 67-771, AIAA, Oct. 1967.

7. Howard, L. R.: Overall Analysis of Commercial V/STOL Systems. Paper 67-969, AIAA, Oct. 1967.

8. Deckert, W. H.; and Hickey, D. H.: Summary and Analysis of Feasibility-Study Designs of V/STOL Transport Aircraft. J. Aircraft, vol. 7, no. 1, Jan.-Feb. 1970, pp. 66-72.

9. Anon.: V/STOL Transports Under Study by Lufthansa, German AF. Vertical World, vol. 5, no. 1, Jan.-Feb. 1970, pp. 14-17.

10. Hill, T. G.: An All Turbofan VTOL or STOL Intercity Transport. Paper 69-1039, AIAA, Oct. 1969.

11. Kappus, P. G.: Design Concept for a V/STOL Intercity Jet. Paper 69-200, AIAA, Feb. 1969.

12. Posner, D. L.: Commercial VTOL Transport Design, Operation and Economics. Paper 67-970, AIAA, Oct. 1967.

13. Coty, U. A.; and Kesling, P. H.: V/STOL and STOL for Short-Haul Transportation. Paper 67-941, AIAA, Oct. 1967.

14. Beeler, E. F.; and Volk, L. J.: Lift Fan Propulsion Systems - V/STOL Aircraft Control. Paper 650831, SAE, Oct. 1965.

15. Stadler, J. P.: The Attitude Control System as an Integral Part of the V/STOL Propulsion System Installation. Paper 70-GT-31, ASME, May 1970.

16. West, R. G.: Fan Lift in VTOL Design. Aeronautical J., vol. 73, no. 704, Aug. 1969, pp. 657-664.

17. Wilde, G. L.: Engines for VTOL/STOL Application. Ann. N. Y. Acad. Sci., vol. 154, art. 2, Nov. 1968, pp. 590-618.

18. Coplin, J. F.: Design Aspects of Power Plants for V/STOL Aircraft. Paper 67-GT-7, ASME, Mar. 1967.

19. Davies, D. O.; and Coplin, J. F.: Some VTOL Powerplant Design and Development Experience. J. Roy. Aeron. Soc., vol. 70, no. 671, Nov. 1966, pp. 977-986.

20. Wilde, G. L.; and Coplin, J. F.: Lift Turbo-fans. J. Roy. Aeron. Soc., vol. 69, no. 656, Aug. 1965, pp. 553-566.

21. Pickerell, D. J.; and Cresswell, R. A.: Powerplant Aspects of High-Speed, Inter-City VTOL Aircraft. J. Aircraft, vol. 5, no. 5, Sept.-Oct. 1968, pp. 467-472

22. Sens, W. H.; and Meyers, R. W.: New Generation Engines - The Engine Manufacturer's Outlook. Paper 680278, SAE, Apr. 1968.

23. Asmus, F. J.: Design and Development of the Tip Turbine Lift Fan. Ann. N. Y. Acad. Sci., vol. 107, art. 1, 1963, pp. 147-176.

24. Kutney, J. T : Propulsion System Development for V/STOL Transports. J. Aircraft, vol. 3, no 6, Nov.-Dec. 1966, pp. 489-497.

25. True, H. C.: The Turbotip Lift Fan VTOL Propulsion System - After the First Generation. Paper 115, American Helicopter Soc., May 1967.

26. Przedpelski, Z. J : Lift Fan Technology Studies. NASA CR-761, 1967.

27 Beeler, E. F ; and Przedpelski, Z J.: Lift Fan Design Considerations. Ann. N Y. Acad Sci , vol 154, art 2, Nov. 1968, pp. 619-640.

28 Volk, L. J : LF-336A High Pressure Ratio Lift Fans. Rep R69AEG180, General Electric Co. (NASA CR-73387), Apr. 1, 1969.

29. Immenschuh, W T.: XV-5A-A Lift Fan V/STOL Research Aircraft. Verti-Flite, vol. 11, May 1965, pp 2-9.

30. Schaub, U W.: Experimental Investigation of Flow Distortion in Fan-in-Wing Inlets. J. Aircraft, vol. 5, no. 5, Sept.-Oct 1968, pp. 473-478.

31. Gregory, N.; Raymer, W. G.; and Love, E. M.: The Effect of Forward Speed on the Inlet Flow Distribution and Performance of a Lifting Fan Installed in a Wing. Rep. R & M-3388, Aeronautical Research Council, Great Britain, 1965.

32. Schaub, U W.; and Bassett, R W : Analysis of the Performance of a Highly Loaded 12-Inch VTOL Z-Axis, Fan-in-Wing Model at Zero Forward Speed. Rep LR-439, National Research Council of Canada, Sept. 1965.

33 Fowler, H. S.: Some Tests of 12-Inch-Diameter Model VTOL Fans. Rep. LR-367, National Research Council of Canada, Feb. 1962.

34. Stockman, N. O.; and Lieblein, S.: Theoretical Analysis of Flow in VTOL Lift Fan Inlets Without Crossflow NASA TN D-5065, 1969.

35 Stockman, N. O.: Potential Flow Solutions for Inlets of VTOL Lift Fans and Engines. Analytic Methods in Aircraft Aerodynamics. NASA SP-228, 1969, pp. 659-681.

36. Hickey, D. H.; and Hall, L. P.: Aerodynamic Characteristics of a Large-Scale Model with Two High Disk-Loading Fans Mounted in the Wing. NASA TN D-1650, 1963.

37. Kirk, J. V ; Hickey, D. H.; and Hall, L. P.: Aerodynamic Characteristics of a Full-Scale Fan-in-Wing Model Including Results in Ground Effect with Nose-Fan Pitch Control. NASA TN D-2368, 1964.

38. Hickey, D H.; Kirk, J V.; Hall, L. P.: Aerodynamic Characteristics of a V/STOL Transport Model with Lift and Lift-Cruise Fan Power Plants. Conference on V/STOL Aircraft NASA SP-116, 1966, pp. 81-96.

39. Turner, R. C.; and Sparkes, D. W.: Tests on a Simulated Lifting Fan System with Inlet Crossflow. Rep. R & M 3461, Aeronautical Research Council, Great Britain, 1964.

40. Hackett, J. E.: Wind Tunnel Tests on a Streamlined Fan-Lift Nacelle. Rep. R & M 3470, Aeronautical Research Council, Great Britain, 1965.

41. Gregory, N.; and Love, E. M.: Wind Tunnel Tests on a Nacelle Fitted with Two Lifting Fans in Tandem. Rep. R & M 3494, Aeronautical Research Council, Great Britain, 1966.

42. Goldsmith, R. H.; and Hickey, D. H.: Characteristics of Lifting-Fan V/STOL Aircraft. Astron. Aerospace Eng., vol. 1, no. 9, Oct. 1963, pp. 70-77

43. Hickey, D. H.; and Cook, W. L.: Aerodynamics of V/STOL Aircraft Powered by Lift Fans. Fluid Dynamics of Rotor and Fan Supported Aircraft at Subsonic Speeds. CP No. 22, AGARD, Paris, France, Sept. 1967, Paper No. 15.

44. James, H. A.: Generalized Characteristics of Vertifan Aircraft in the Fan Mode. Ann. N. Y. Sci., vol. 154, art. 2, Nov. 1968, p. 196.

45. McKinney, M. O.; and Newsom, W. A.: Fan V/STOL Aircraft. Ann. N. Y. Acad. Sci., vol 154, art. 2, Nov. 1968, pp. 872-892.

E-5614-2

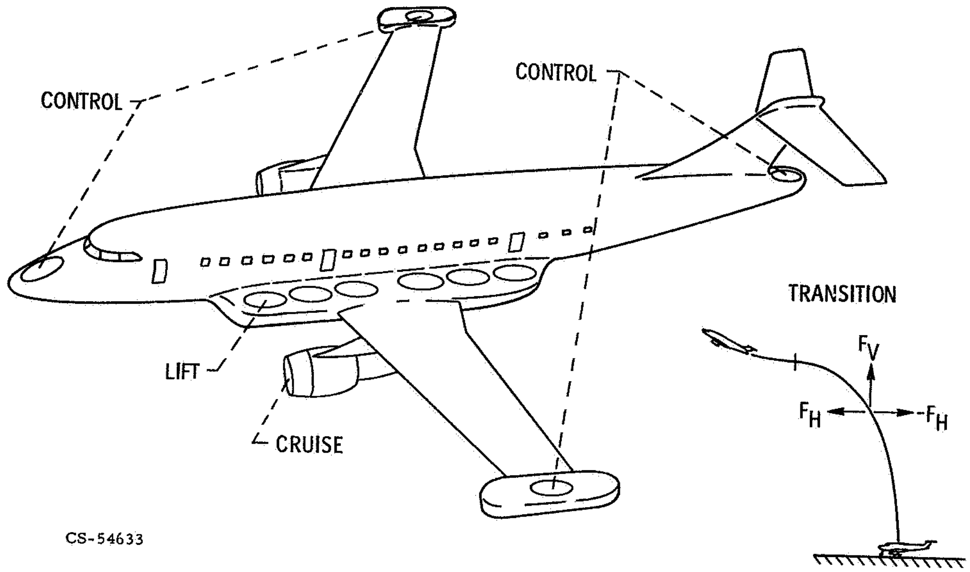


Figure 1. - VTOL propulsion functions.

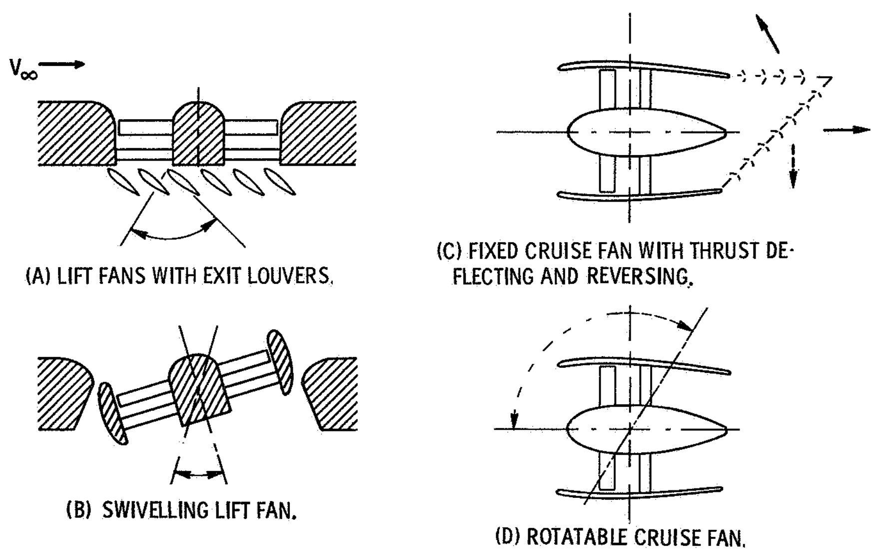


Figure 2. - Methods of providing horizontal thrust for transition flight with fans.

E-5614-2

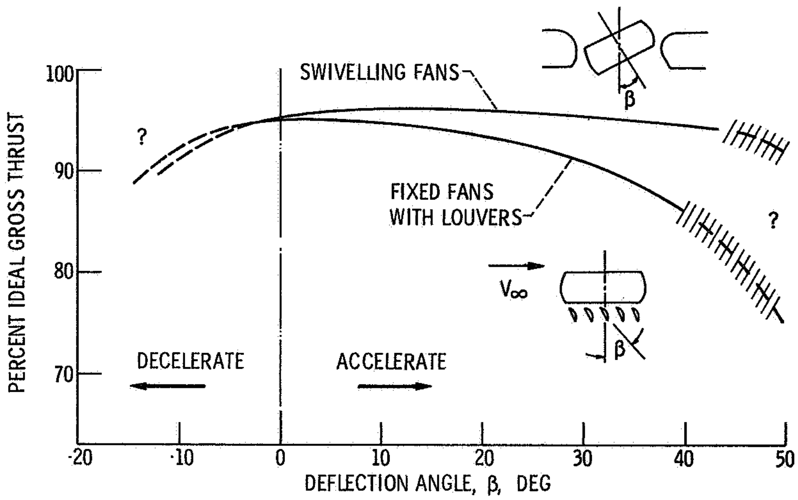


Figure 3. - Lift fan thrust vectoring in crossflow.

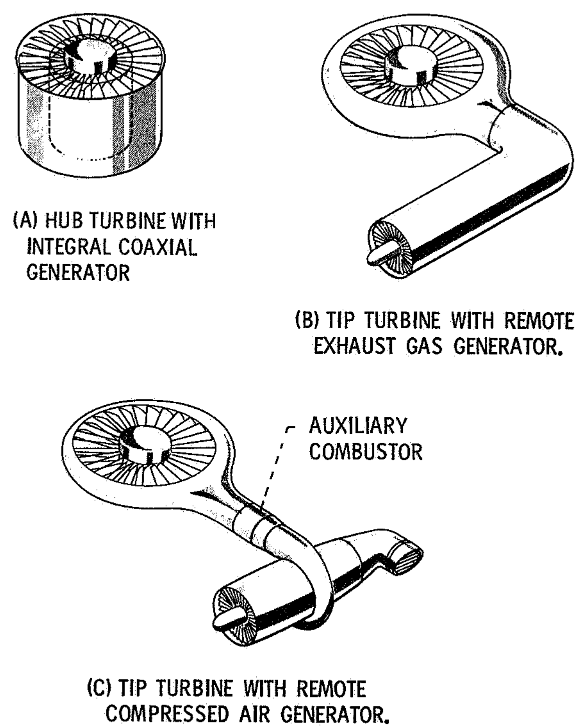


Figure 4. - Lift fan drive systems.

E-5614-2

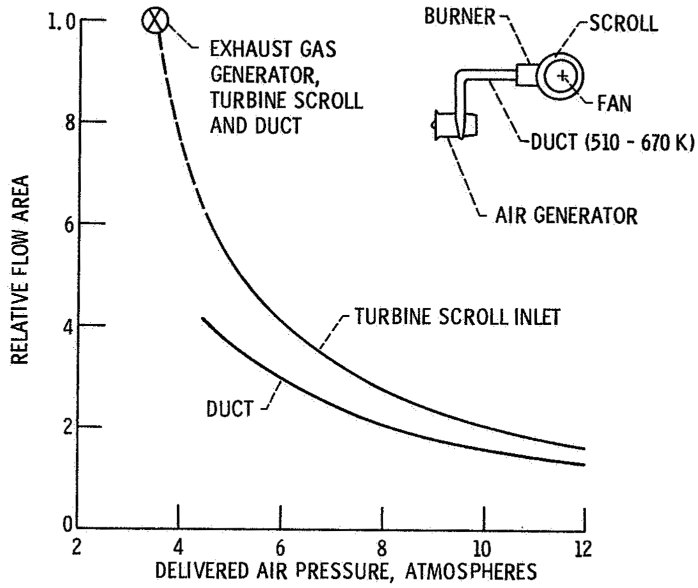


Figure 5. - Remote air generator system flow areas. Flow Mach number = 0.3. Fixed fan design. Fan turbine inlet temperature = 1900° R (1055 K).

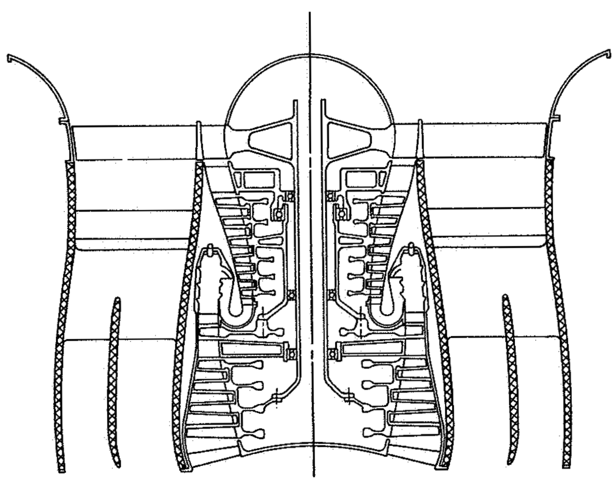
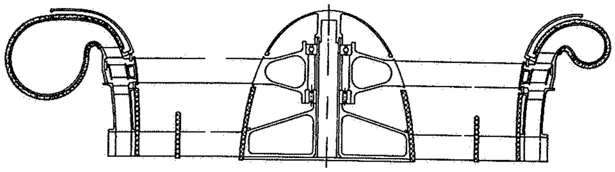
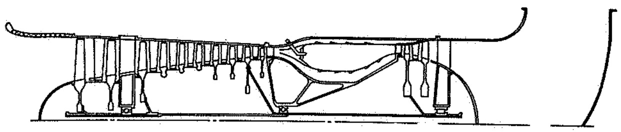


Figure 6. - Integral coaxial lift fan system.

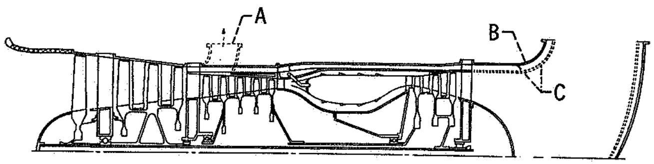
E-5614-2



(A) FAN WITH SINGLE-STAGE TIP TURBINE.

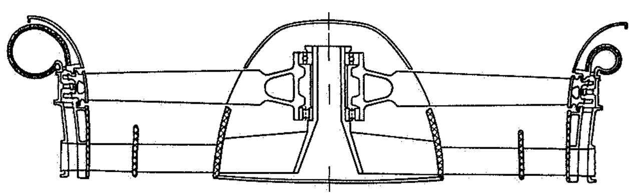


(B) STRAIGHT JET GAS GENERATOR.

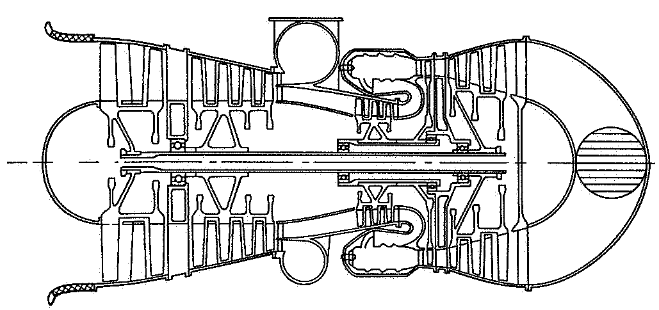


(C) LOW BYPASS GAS GENERATOR.

Figure 7. Remote lift fan system with exhaust gas generator.



(A) FAN WITH TWO-STAGE TIP TURBINE.



(B) TWO-SPOOL BLEED AIR GENERATOR.

Figure 8. - Remote lift fan system with compressed air generator.

E-5614-2

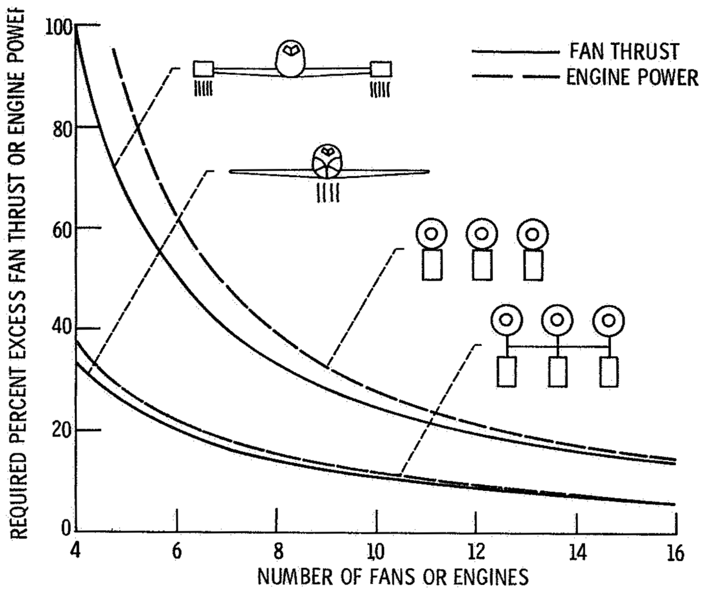


Figure 9. Required overdesign for fan or engine failure. Limiting situations: maintain symmetrical thrust, normal acceleration and control.

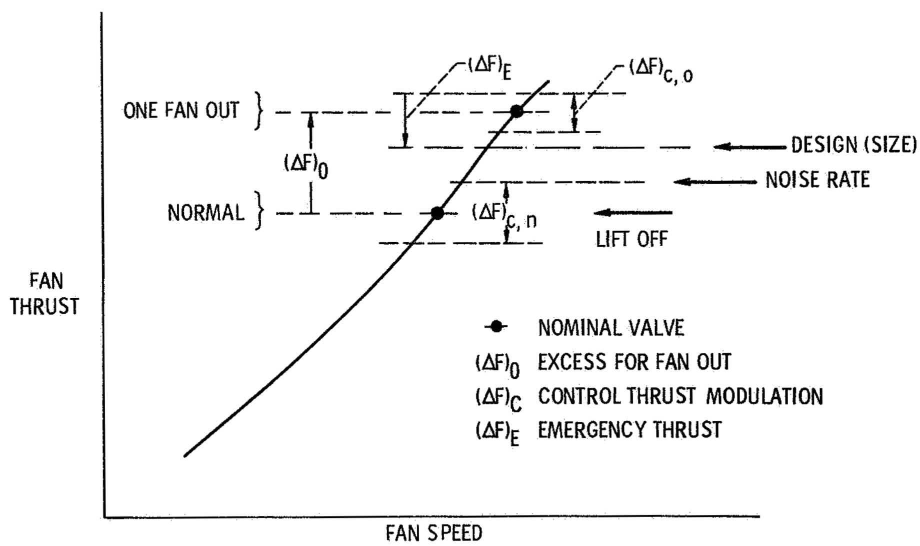


Figure 10. - Illustration of fan operating points for multifan VTOL transport.

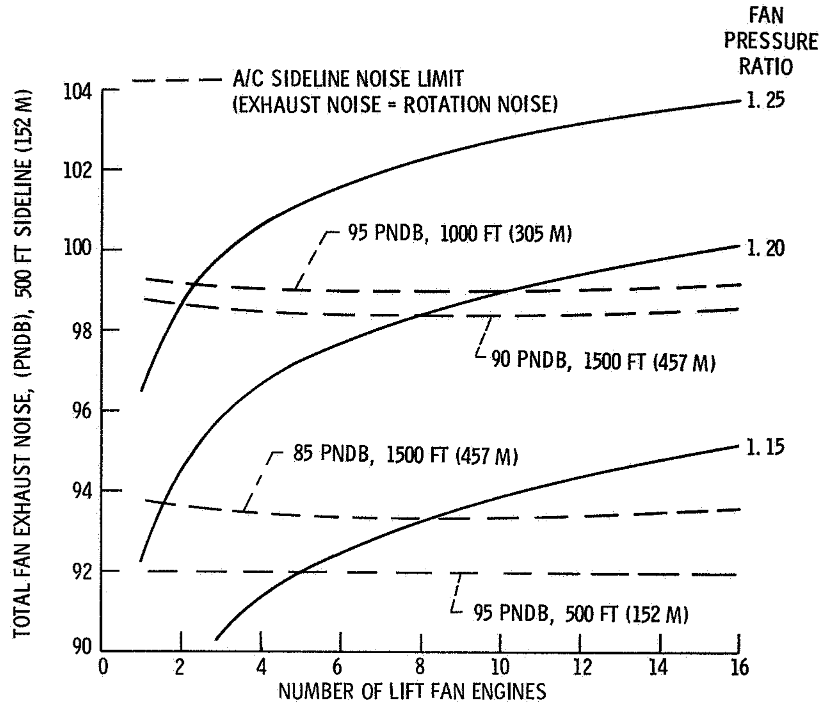


Figure 11. - Lift fan exhaust flow noise. Integral lift fan engines with $V_T/V_F = 1.2$; V^8 jet noise model with $V_\infty = 0$; 100 000 lb total thrust (45 359 kg).

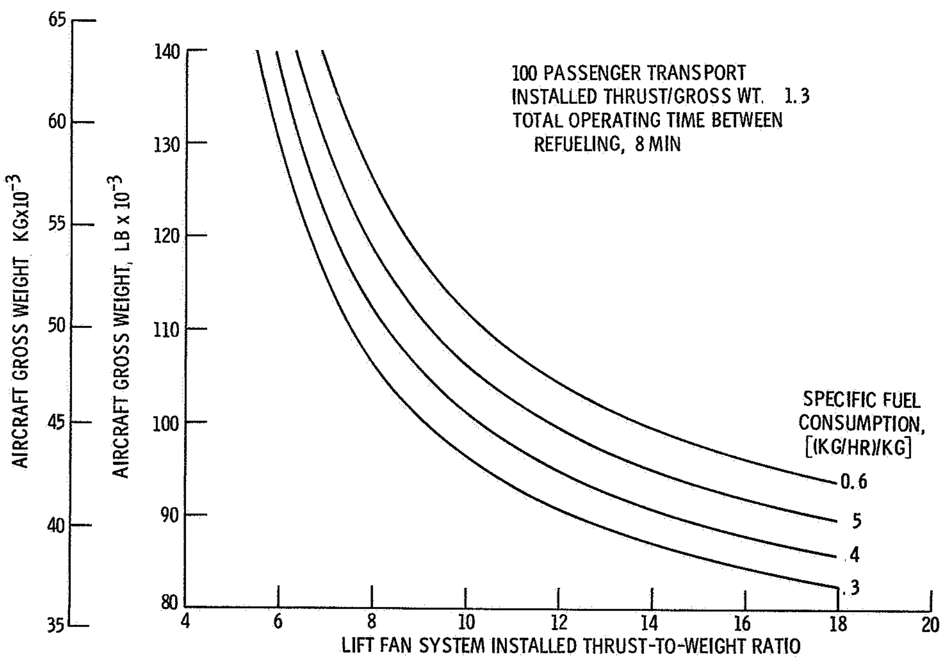


Figure 12. Effect of lift fan system installed thrust-to-weight on airplane gross weight.

E-5614-2

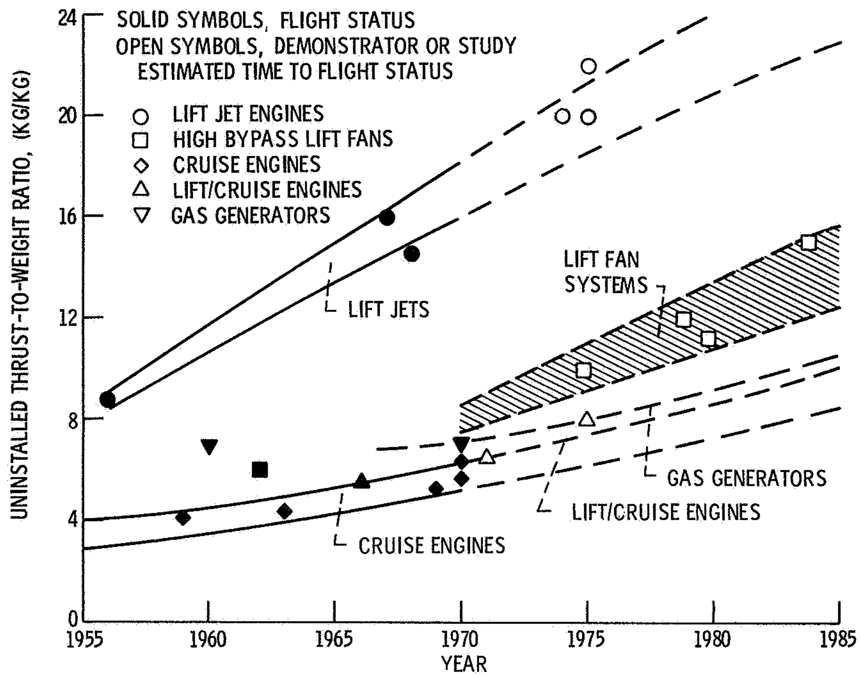


Figure 13. Trends in engine uninstalled thrust-to-weight.

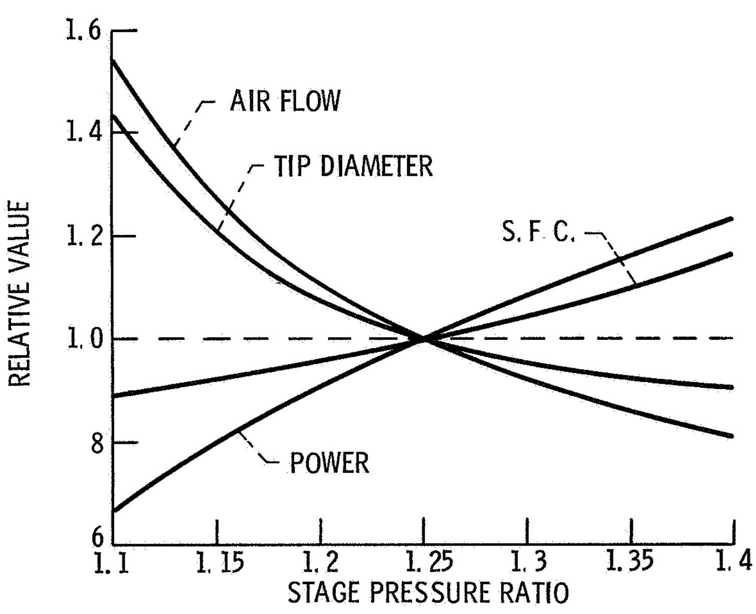


Figure 14. - Lift fan characteristics - variation with stage pressure ratio.

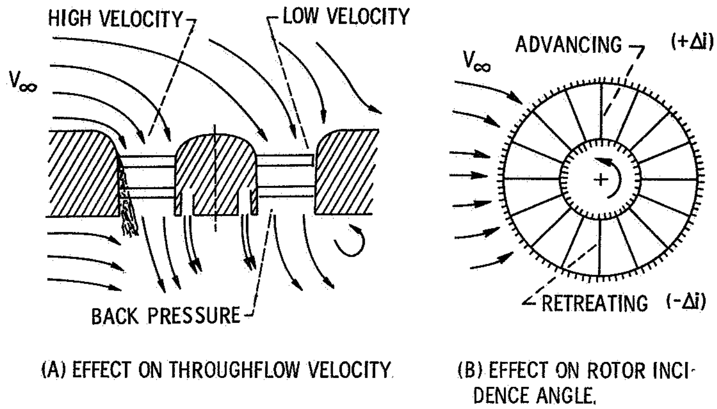


Figure 15. - Lift fan inflow in crossflow.

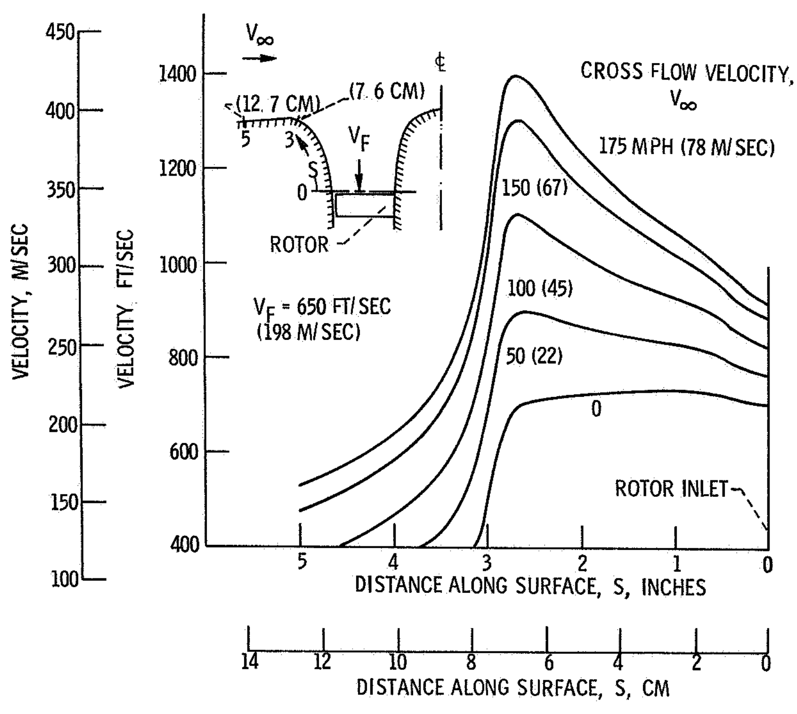


Figure 16. Theoretical surface velocity on inlet bellmouth in crossflow.

E-5614-2

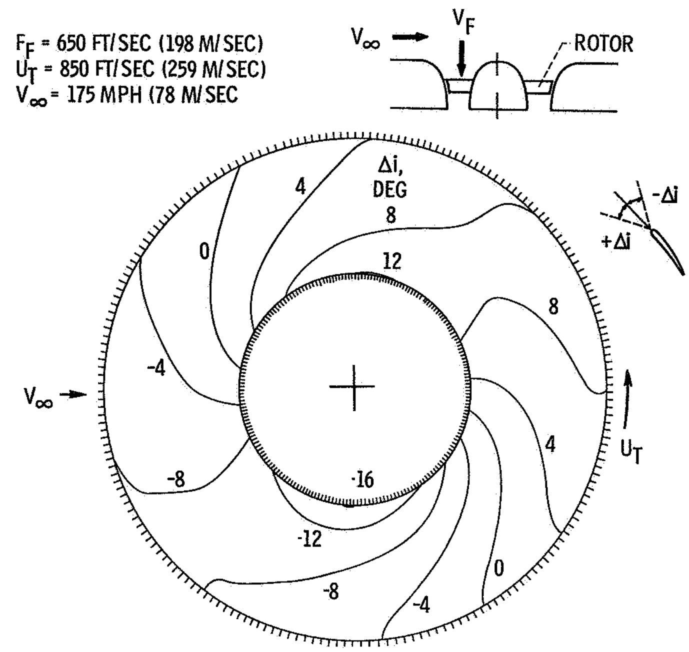


Figure 17. - Theoretical change in rotor incidence angle due to crossflow.

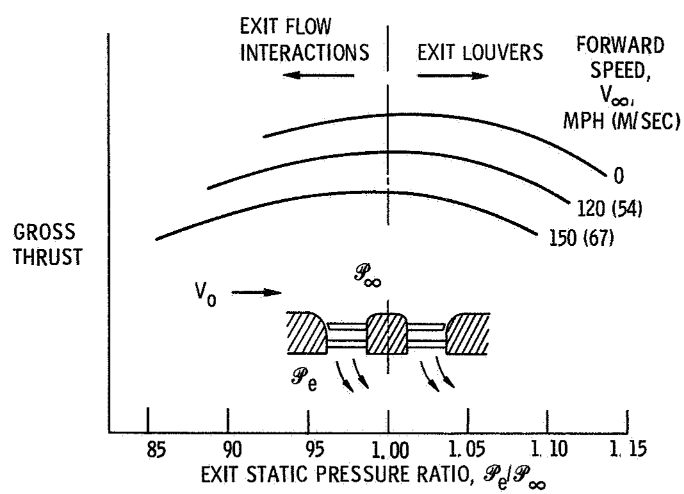


Figure 18. Effect of fan back pressure.

E-5614-2

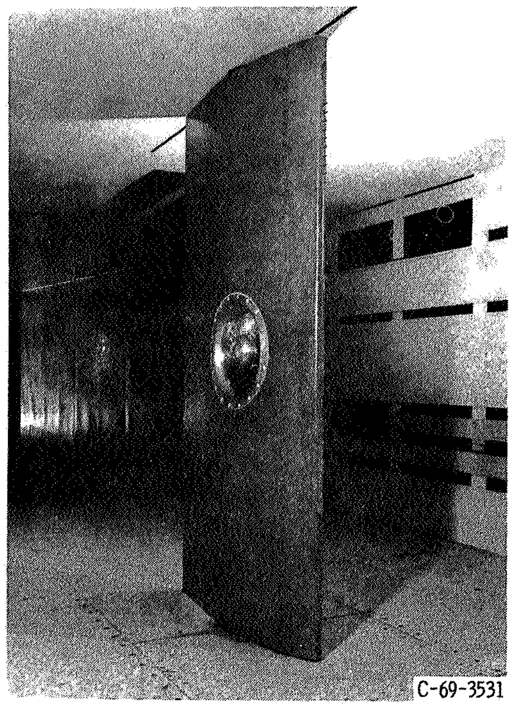


Figure 19. Model lift fan-in-wing in NASA Lewis Research Center V/STOL tunnel.